



Energy, Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

CANMET

Canada Centre
for Mineral
and Energy
Technology

Centre canadien
de la technologie
des minéraux
et de l'énergie

DEWATERING AND SELF DEWATERING OF CONCENTRATES PART C - LITERATURE REVIEW

M.J. Stefanski
Mineral Processing Laboratory

May 1987

Project: 30.13.02
Iron Ore Processing

77PP

MINERAL SCIENCES LABORATORIES
DIVISION REPORT MSL 87-79 (IR)

This document is an unedited
interim report prepared primarily
for internal and internal
reporting purposes. It does not
represent a final expression of
the opinion of the Canada Centre
for Mineral and Energy Technology
(CANMET).

MICROMEDIA

Ce document est un rapport
provisoire non-révisé et rédigé
principalement pour l'usage
interne et de documentation
interne. Il ne représente aucun-
ment l'expression définitive de
l'opinion du Centre canadien de
la technologie des minéraux et de
l'énergie (CANMET).

DEWATERING AND SELF DEWATERING OF CONCENTRATES
PART C - LITERATURE REVIEW

by
M.J. Stefanski

INTRODUCTORY NOTE

This paper is a continuation of the Mineral Sciences Division Report MSL 87-29 (IR). However, as it consists mainly of a literature review and discussion on the present state of theory and knowledge in the field of dewatering/ water migration/moisturizing of fine bulk materials, it can be read as a separate, independent work.

SUMMARY

The literature review consists of 83 items covering mostly the period 1960-1985. Each item includes a short summary underlining and commenting on features relative to the dewatering/water migration processes of fine bulk materials and in particular of Canadian iron ore concentrates. Discussion of the present state of theory and knowledge, as presented in this report, leads to conclusions and recommendations tabled in the "Long Range Program for Further Investigations", which could be carried out to the benefit of the Canadian Iron Ore Industry.

Keywords: dewatering of fine bulk materials, dewatering, filtration, centrifuging of iron ore concentrates, moisture migration, water sequestering, self draining in fine bulk materials

NOTE LIMINAIRE

Ce travail représente la suite du rapport de la Division des sciences minérales MSL 87-29 (IR) qui a été édit précédemment. Puisqu'il est composé surtout de la revue de littérature et la discussion sur l'état présent de théorie et science dans le domaine d'essorage/migration d'eau/humidification des matériaux fines en vrac, il peut être lû séparément, comme un rapport indépendant.

RÉSUMÉ

La revue de littérature comprends 83 références couvrant surtout la période 1960-1985. Chaque référence est muni d'un bref résumé, soulignant et commentant les problèmes de procédés de déshydratation par moyens mécaniques ainsi que de migration d'eau dans des matériaux fines en vrac. Il fait référence surtout aux procédés concernant les concentrés de minerais de fer canadiens.

La discussion sur l'état actuel de la théorie et science, présentée dans ce rapport, conduit aux conclusions et recommandations permettant proposer un "Programme de recherches à long termes" qui pourraient être entreprises au bénéfice de l'industrie canadienne du minerai de fer.

Contents	Page
INTRODUCTORY NOTE AND SUMMARY	i
NOTE LIMINAIRE ET RÉSUMÉ	ii
1. CONCLUSIONS AND RECOMMENDATIONS	1
2. DISCUSSION OF THE PRESENT STATE OF KNOWLEDGE	2
2.1 General Remarks	2
2.2 Porous Media/Water Systems	3
2.2.1 States of fine bulk materials depending on the moisture content	3
2.2.2 Consolidation and porosity	4
2.2.3 Significance of water bridges	5
2.2.4 Water layers and water types	6
2.2.5 Particle size distribution; porosity, specific surface	9
2.2.6 Influence of surfactants	10
2.2.7 Selected properties of fluids and interface characteristics	11
2.3 Capillary Pressure	12
2.3.1 Capillary pressure curve	12
2.3.2 Causes of the capillary pressure	13
2.4 Flow Through Porous Media	14
2.5 Physics of Dewatering/Moisturizing Water Migration Processes	14
2.5.1 Descriptive approach	14
2.5.2 Mathematical approach	18
2.5.2.1 Mathematical models; their usefulness	18
2.5.2.2 Examples of mathematical equations and formulas describing selected features of the process of dewatering/moisture migration	19

Contents (cont'd)	Page
2.6 Sequestering Water	27
2.7 Transportability of Fine, Wet, Bulk Materials	29
3. OVERVIEW OF LITERATURE; LIST OF REFERENCES PROVIDED WITH SHORT SUMMARIES OF FEATURES RELATED TO THE DEWATERING/MOISTURIZING/SELF DRAINING OF FINE BULK MATERIALS	31
SECTION 1. General Knowledge and Theory	31
SECTION 2. References Concerning Iron Ore in Particular	39
SECTION 3. Transport and Storage	43
SECTION 4. Centrifuging	51
SECTION 5. Filtration	53
SECTION 6. Surfactants, Flocculation	60
SECTION 7. Sequestering Water	64
SECTION 8. Pelletizing	67
4. LONG RANGE PROGRAM FOR FURTHER INVESTIGATIONS	71

1. CONCLUSIONS AND RECOMMENDATIONS

1. The capillary pressure curve is a key to understanding processes of water migration, including dewatering by mechanical means. Reliable data for such a curve have to be obtained directly by experiment. For filtration purposes, measuring methods based on pressure should be used while for centrifuging and water migration, centrifuge methods are preferred.
2. No adequate methods of measuring particle properties are known therefore characteristics of a fine bulk material like porosity, specific surface, wettability, consolidation properties, etc. cannot be determined by calculations. They have to be measured.
3. No comprehensive theory has been developed to date which would accurately mathematically describe mechanical dewatering/ moisturizing/water migration processes for real, fine bulk materials. Empirical and semi-empirical formulas do exist and can be used for calculations within limited ranges of values close to experimental data.
4. To obtain basic data for designing and/or forecasting results of industrial processes of dewatering - small scale filtration tests or, where more adequate, centrifuging tests must be carried out.
5. To study self drainage i.e., water migration phenomena, centrifuging can be used. The results should be confirmed by testing the influence of shaking and vibrations on water behaviour in samples of fine bulk material.
6. Filtered iron ore concentrates (from spirals) are in pendular state. Further moisture which can be removed from them exists in form of "water bridges" more or less isolated from each other.

Within the existing industrial equipment used in conjunction with concentrators, residual moisture content can be decreased if the surface tension of water contained in "bridges" is reduced. This can be achieved using an adequate surfactant.

7. Before a surfactant can be introduced for enhancing the dewatering on commercial scale its influence on the transportability of concentrates has to be determined. One of a few known methods of measuring the transportability of wet fine bulk materials should be adapted for this purpose.
8. Water migration (self drainage) in iron ore concentrates can be prevented by the use of peat moss or bentonite as water sequestering agents.

2. DISCUSSION OF THE PRESENT STATE OF KNOWLEDGE

2.1 General Remarks

As already mentioned in the introduction to this report (see part A: GENERAL, page 1), physical and physico-chemical phenomena of dewatering and of porous media like fine grain bulk materials, are studied in connection with several branches of technology and science.

A unique approach, even to one specific material like iron ore concentrate, is not possible yet. There is no unique theory that could give a synthesis of knowledge and a basis for measuring and indicating the behaviour of three phase dispersed systems i.e., solid-liquid-gas under the influence of acting external forces. In many cases deterministic mathematical methods are quite adequate to describe this behaviour but sometimes a stochastic approach would be more efficient. Mechanical and hydro-mechanical approaches must often be replaced by molecular physics or chemical methods.

Probably the most practical and therefore efficient manner would be to treat the subject of study as a "black box with a cover slightly ajar". As far as possible the input and output only should be measured and studied but where no satisfactory

answer is obtained, a deeper "micro", approach, comparable to getting to a certain level inside the black box, would be necessary.

2.2 Porous Media/Water Systems

2.2.1 States of fine bulk materials depending on the moisture content

Five different states of the fine bulk material (iron ore concentrate) can be distinguished [3.1], [2.3].

Dry state. Only "rigid" layers of water, i.e., water bound physico-chemically by adsorption or chemically, is present. The material is dusty and its pore number (pore volume/solid volume) is low when mechanically compacted. No cohesion is observed and the tensile strength of consolidation samples is close to 0 [3.7], [3.1].

Pendular state. Apart from the water bound in rigid layers there is also water bound by capillary forces. It occurs in bridges between the points of contact of particular grains. Inter-molecular forces appearing as surface tension produce capillary pressure. Liquid bridges bind each particle to its neighbours so that particles form a skeletal structure. The compaction becomes looser, the pore number higher. The material is neither sticky nor dusty. The cohesion is high. The filter cake of an iron ore concentrate after dewatering on vacuum or pressure filters is in this state.

Funicular state. Occurs when more water is added so that free liquid water partly fills the pores. The cohesive forces become weaker. The radius of curvature of the capillary surfaces increases. The material is once again packed more densely. Free water on the surface may make the materials sticky.

Capillary state. Pores are completely filled with water, possibly with some air bubbles surrounded by water. There is no excess pressure in the pores.

Particles "suspended" in water layers become closer to each other so that a higher degree of compaction is achieved. The tensile strength of consolidated materials reaches its maximum.

Supersaturated state. Additional incoming water has no room in the capillary state structure, therefore it creates pore pressure which forces the particles apart. They lose contact and the whole material starts flowing. The tensile strength falls dramatically to 0.

During vacuum or pressure filtration iron ore concentrate changes successively from the supersaturated, through capillary and funicular, to the pendular state.

Filtered concentrate is loaded onto railway cars in the pendular state. Particular water blobs are isolated from each other to a great extent. During its way to the port and later in ship holds the material is shaken and vibrated. This action combined with the gravity forces makes the water blobs descend and creates a supersaturated state with free water flowing at the bottom of cars or ship holds.

This process is enhanced by the consolidation of the material. The concentrate becomes more compact closer to the bottom. Pores become smaller and the difference of capillary pressure helps to precipitate water down.

2.2.2 Consolidation and porosity

The consolidation of any fine bulk material, i.e., denser packing of grains which involves increasing the relative density (and unit weight) with simultaneous decreasing of the pore number (and the dimension of pores), depends not only on mechanical load or pressure applied but also on the moisture content. This relation is usually shown by a compaction curve which can be obtained from compaction tests done with Proctor apparatus [1.4], [3.1], [3.2], [3.3], [3.4], [3.19].

The consolidation process is different for different particle size distributions and different grain shapes. The porosity of fine bulk materials depends on so many factors that in practical terms when a given material is characterized by its particle size distribution, specific weight, grain shape factors (sphericity) and moisture content, it is impossible to calculate exactly either the pore number (void ratio) or the pore size distribution. For all practical purposes, the porosity of material such as iron ore concentrate has to be measured [5.2], [1.17], [5.7].

Calculation of the porosity is possible using only idealistic and simplified mathematical models. For real materials this gives very inaccurate and therefore unsatisfactory results. For calculations connected with the dewatering of iron ore concentrates, porosity should instead be treated as one more characteristic of the material, although it changes depending on other factors.

2.2.3 Significance of water bridges

For an understanding of the process of dewatering/ moisturizing of dispersed systems and especially for problems of further dewatering of filtered iron ore concentrates, the physics of water bridges is of particular importance. The volume of water bridges, capillary pressure and forces binding particles together are the most important factors.

Although in recent years some progress in calculation of these factors was achieved [1.2], purely theoretical approaches using models which are based on the geometry of simple ideal solids i.e., spheres, cones, cylinders and planes, give only approximate results; the smaller the bridges are the more inaccurate the results. Much better results can be achieved by experiments.

2.2.4 Water layers and water types

Adsorbed water, i.e., water occurring in the layers closest to the surface of a solid body, behaves differently than free water. For example, heating in an oven to 350°C does not evaporate all such water and cooling to -40°C in many cases does not make it freeze. Therefore, it is justified to speak about different types of water or different waters. Two, three, four or more layer models are used to describe these types of water.

In soil mechanics for construction and civil engineering purposes as well as for transport, mechanical dewatering and some other techniques, the simplest two layer model is predominantly used [1.12], [1.13], [7.5], [1.5], [3.1], [3.2], [3.3], [3.19].

Two types of water are distinguished: "rigid" or "rigidly bound" water and mechanically removable water. The latter can be further sub-divided into capillary and free water.

It is practically impossible to remove mechanically from mineral concentrates the "rigid" water. Zenkov [1.5] claims that even forces 70,000 times larger than gravity would not be sufficient for this purpose. For users of two layer models it is common practice to assume that rigid water is equally spread over the surface of solid particles. If the thickness of this layer is known one can easily calculate, for a given material, the volume of residual moisture impossible to remove even by the most efficient filters or centrifuges. Of course the grain size distribution or, better, the specific surface as well as the shape factor of the material must be known. Some authors arbitrarily assign the thickness of the rigid water layer within a given range, e.g., 50 to 5 μm [1.5], 0.2 μm [3.1], 0.1 μm [1.12], 1 μm [1.13] or express its thickness by multiples of water molecule size, e.g. 20 to 200 [1.13], or 10 [7.1] water molecules.

Some authors [7.1] classify water as chemically or physically (through van der Waals forces) bound when the binding energy is in excess of 0.5 kJ/mol. Almost all authors state that the thickness of the "rigid" water depends on the kind of solid and its surface, as well as on particle size ([1.5], [1.13], [7.1] and others).

The two layer model is simple and may prove to be sufficient for many applications in the field of dewatering/water migration of dispersed media. However the explanation of the use and action of surfactants, the physics of the surface tension and capillary forces, or of the water sequestering by peat moss and bentonite requires "getting deeper into the black box" and using more complex multi-layer models.

The physico-chemistry of hydration layers is a vast domain of science and only very few aspects can be mentioned here.

Depending upon the amount of energy used in binding water, the following four kinds of water can be distinguished [1.10], [7.1]: 1) free (or volume or mechanically entrained) water, 2) water bound physically and physico-mechanically (or capillary), 3) water bound physico-chemically, and 4) water bound chemically. Some authors distinguish other categories like osmotically bound water, hydration water, hydrogen bonded water and structural water which would fit into the four kinds of water, already mentioned [7.1].

1. Free water is generally not influenced by the solid (mineral) surface.
2. Water bound physically and physico-mechanically is under the influence of osmotic and capillary bonds. The strength of the bonds depends on the dimensions of the

capillaries. Within this category bridge water and capillary flow or capillary head water can be distinguished [1.1].

Water bridges play a significant role in binding mineral particles to each other, i.e., creating cohesion and tensile strength of consolidated, fine, bulk material. In this respect "liquid bridge forces are about four times as large as the van der Waals forces which are an order of magnitude greater than electrostatic adhesion forces between conductors, due to contact potential, and these are again about 100 to 10 times as great as adhesion forces due to maximum surplus charges of opposite sign" [5.5].

Water bridges are of particular importance for this work since residual moisture of filtered iron ore concentrate occurs mainly in this form.

3. Water bound physico-chemically (adsorption water) forms mono and polymolecular layers on external (and internal inside pores and between packets) surfaces of solid particles (minerals). Adsorption of this water results from the action of intermolecular van der Waals forces, hydrogen bridge bonds as well as forces of dipole orientations of induction and dispersion. The adsorption water forms the first external layer adhering to capillary walls and edges of (mineral) particles. The energy of water adsorption bonds is nearly one order of magnitude smaller than the energy of chemical bonds [1.10].

Mineral surfaces [1.10], [1.15], [1.3] are not evenly active, e.g., hydrophilic or hydrophobic everywhere. There is a distribution of active centres on the surface which can be quantified and influenced (with surfactants for example). Under the influence of the field of forces of such active centres the adjacent molecules of adsorbed

water tend to be oriented. The state of molecules depends on their distance from the surface and on the distribution of active centres. The state of energy of adsorbed water molecules is not homogenous. The molecular structure of this water is disturbed in comparison with a homogenous structure of free water [1.10]. This results in differences of physical properties of these two kinds of water.

4. Water bound chemically. Its adherence to the mineral surface is by far the strongest. Crystalline water and other hydration waters like water bound by hydroxyl groups and others [1.10] belong to this category.

In the two layer model, waters bound physico-chemically and chemically are together called rigid water.

2.2.5 Particle size distribution; porosity, specific surface

Particle size distribution of the porous material (iron ore concentrate) is of the highest importance to this work. Particle size determines the specific area and porosity of the system. The higher the specific area, the thicker the rigid water layer and therefore the higher the residual moisture of the filter or centrifuge cake.

"Porosity", unless indicated otherwise, means in this work the structure, dimensions and distribution of external pores, i.e., of the spaces between particles. Micropores and transitional pores, i.e., pores with a radius smaller than $0.1 \mu\text{m}$, [1.16] occurring inside particular particles and creating internal specific areas can be filled almost exclusively with "rigid" water. They may influence the hydrophobicity/hydrophylicity ratio of a particular surface and possibly influence the action and consumption of surfactants used

in the dewatering process, but they do not directly take part in the mechanical process of dewatering or water migration.

For studies of the mechanical aspect of dewatering fine bulk materials or of water migration, it is more appropriate to measure the specific area with the Blaine permeameter than use the BET gas adsorption method. The gas adsorption method gives significantly higher results because it measures not only the external surface area but also the internal surface of micropores and transitional pores, as well as different micro cracks and cavities [1.17], [1.15].

2.2.6 Influence of surfactants

It is a common practice to use surfactants as "filter aids" or "centrifuge aids"; however, their action aims mainly at increasing the solid weight recovery. Only few substances, under certain conditions, help to decrease the residual moisture [6.4].

On the contrary, the use of flocculants may "thicken the rigid layer of water" and therefore raise the residual moisture content. It can also diminish the water migration effect wherever needed. For decreasing the residual moisture, polymers with lower molecular weight could be more appropriate [6.4]. Most surfactants used for mineral processing significantly decrease the surface tension of water [2.9]. One would expect that this should automatically result in liberation of blobs and bridges of residual water and enable their removal. However, no direct correlation between the use of surfactants and residual moisture decrease was found [2.9]. The action of flocculants and other surfactants is not that simple. The energy terms of interactions between particles can be explained as consisting of two components - overlapping of double layers leading to

repulsion, and arising from London dispersion forces leading to van der Waals attraction [6.1]. Flocculating agents modify these energy terms or introduce new interaction terms. Five different general modes can be distinguished by which flocculant agents act, disturbing the existing equilibrium and introducing a new one [6.1]. More than one action may be involved simultaneously. The volume of physico-chemically bound water in some cases can be reduced, in others increased, by the use of surfactants.

2.2.7 Selected properties of fluids and interface characteristics

Dewatering of mineral concentrates and water migration should be treated as a three phase phenomena. Characteristics and behaviour of all three phases as well as their interaction must be taken into account for adequate description of these processes. Avoiding a deeper and more complex look into thermodynamic and mechanical definitions of interfaces [1.2] (boundary surfaces of particular phases) one can simply say that the most important characteristics are the surface tension and the viscosity of the liquid phase (water), the compressibility of the gas (air) and as concerns the interactions the wettability of solids by the liquid phase. This latter results from the distribution of hydrophilic versus hydrophobic active centres on the mineral surface.

Theoretically the wettability could be measured on the boundary line between three phases by the wetting angle. However, practical use of the wetting angle as an index is very limited because of difficulties in measuring it exactly. It shows hysteresis, depends on roughness of the surface and is deformed on sharp edges. When the interface line moves the observed dynamic wetting angle differs significantly from the static one [1.2].

In spite of this the wetting angle is so useful for theoretical work that a conception of an "effective

wetting angle" has been introduced. It has been calculated from the capillary pressure rather than measured [1.2].

The liquid is wetting the solid phase (the solid is hydrophillic) when the angle is $\delta < 90^\circ$; liquid bridges are then attracting particles to each other. The contrary occurs when $\delta > 90^\circ$.

2.3 Capillary Pressure

2.3.1 Capillary pressure curve

The capillary pressure curve is a key to understanding the processes of dewatering by mechanical means and of moisture migration. [1.2], [5.7], [1.1], [5.2], [5.3], [1.11], [1.4].

It shows the relation between the capillary pressure and the amount of liquid contained in the porous system. In technical literature, cases can be found where authors assume, for calculations, that the capillary pressure of a given porous system is constant irrespective of the moisture content. Such assumptions are inadmissible. In reality, similarly to the particle size distribution, the capillary pressure represents also a distribution which has to be measured [1.2], [1.4], [5.7] if the capilarity characteristics of a given material are to be presented.

To date, neither the porosity - geometry of spaces between particles nor the capillary pressure can be satisfactorily calculated from a given particle size distribution and other characteristics of a real material.

The static capillary pressure curve shows a hysteresis which can be explained by the existence of micro pores and "pore bottle-necks".

It should be mentioned that even in very homogeneous real fine bulk materials the distribution of moisture does not have to be uniform. Different states of the

material, depending on local moisture content, may co-exist in equilibrium [1.2] so that the capillary pressure curve gives only an average picture.

Co-ordinates for state capillary pressure curves are usually measured with pressure apparatus [1.2], [1.4]. Many different pressure instruments are described in the literature but all of these are based on the principle of von Heines (1927) [1.2]. Another measuring method is based on centrifugal tests. In centrifuges the hydrostatic equilibrium is established faster so that centripetal methods take less time. For considerations concerning filtration - pressure method should be used; while for centrifuging or self draining - centrifuge method are better suited. Phenomena linked with the hysteresis of dewatering/soaking result, i.e., in the fact that the "history" of a given material (sample) influences the capillary pressure curve. In some cases, this can result in getting non-reproducible results of experiments.

Capillary pressure curves can serve, to estimate the approximative value of residual moisture content [1.2].

2.3.2 Causes of the capillary pressure

There are many theories explaining the existence of the capillary pressure [1.2], [1.10]. A simple and convincing explanation is given in [1.10]. It is based on thermodynamics of thin hydration layers on solids.

Water layers close to the solid surface have a more orderly structure. Their state of energy is lower than the energy state of free water. Borders of a meniscus should be treated as a thin hydration layer where molecules of water are oriented by surface forces of the solid body. The vapour pressure over such a layer is lower than over the plain surface of free water. Free molecules of unbound water tend to travel towards the

oriented-and-captured water at the meniscus border according to the principles of thermodynamics. In a capillary tube, "in front of" the meniscus layer is the other wall of the capillary with another thin layer of water having equally lower vapour pressure.

Autodiffusion makes molecules of water drift from thicker to thinner layers making water raise, independently from the gravity forces, until a dynamic equilibrium with the gravity is established.

2.4 Flow Through Porous Media

Hydromechanics of the flow during dewatering/moisturizing of fine bulk materials is an integral part of the process. The basic principle to which most contemporary authors refer in describing physically dewatering processes is Darcy's law. It was established in its original form in 1856 [1.11], [1.12], [5.2], [1.13], [5.1], [5.4], [5.7]. The differential equation which is now commonly called Darcy's law is not a true expression for Darcy's experimental findings but a more general form from which the original expressions may be easily derived [1.11]. Darcy's law describes basically the flow of homogeneous fluids in porous isotropic and incompressible media. Successful generalizations were also attempted assuming that porous media are anisotropic and compressible. It was very successfully used for defining the permeability of soils and other packed beds, developing the theory of filtration and many others.

2.5 Physics of Dewatering/Moisturizing Water Migration Processes

2.5.1 Descriptive approach

Dewatering by filtration consists mainly in pushing out water from the pore system by air under pressure. The process starts [1.1] when the air pressure is higher than the capillary pressure. Not only the free capillary water is removed but also bridge water and other physico-

mechanically bound water. The higher the speed of air in capillaries the more physico-mechanically bound water is removed. Batel [1.1] distinguishes three different periods of dewatering by filtration which explain the shape of the curve of kinetics. During the first period a "capillary flow" is dominant. During the second period both the capillary and "film flow", while during the third only the film flow occurs. Other authors [5.3], [5.4] distinguish two parts of the filtering process: 1) piston flow 2) dewatering by air-flow-through. The higher the pressure difference the shorter the time needed to reach a given residual moisture. According to some authors [1.2], [5.7], [5.4] the piston flow does not exist in reality. The dewatering starts in these areas where pores are the largest and consequently the capillary pressure the lowest. Further dewatering proceeds when the pressure raises. So the capillary water is removed step by step. This way, thanks to availability of interconnected pores systems an average uniform flow occurs which for theoretical considerations can be regarded as equivalent to a "piston flow". For diminishing the residual moisture the last phase of dewatering is important. The air flow through a partially dewatered bulk material is different from the flow through a dry material. It can be described with the help of the conception of relative permeability. The permeability to gas changes as the dewatering progresses [5.7].

For concentrates of iron, copper, zinc and different coals the minimum air pressure, (threshold pressure) equivalent to the lowest values of capillary pressure needed to start the filtration process is about 0.3 to 0.5 bar [5.4]. "As the differential pressure for vacuum filtration can only amount to $\Delta p = 0.8$ bar only small and insufficient residual moisture decreases are

possible, especially in the area (range, M.S.) of technically applicable dewatering times" [5.4]. However, significant improvement can be achieved when the differential pressure is increased as occurs in pressure or hyperbar (both pressure and vacuum) filtration.

The physics of the second phase of dewatering by filtration, when the air flows through a partially dewatered material, is not satisfactorily theoretically explained to date [5.3]. The longer the air is flowing through the material the lower is the residual moisture but the rate of dewatering becomes very low after a certain time. Limits are determined rather by economic than by technical factors. The higher the pressure difference the shorter is the time needed for lowering the residual moisture, but higher pressure differences than 3-4 bars are again uneconomical.

Experiments show that in practice the filter cake cannot be considered as incompressible. In other words the porosity and permeability of the cake depend on the pressure difference [5.7]. This means that most models used for calculations of the filtration processes assuming an incompressibility of the cake are not satisfactory. Even such a widely used and proven equation like Darcy's law is generally not exact and can be considered as correct only within certain limits.

In general, the calculation of such cake characteristics like permeability, porosity and flow resistance of filter media exclusively from the grain size distribution is impossible. The same limitation concerns the calculations of the capillary pressure distribution. In order to get good accordance with experimental results the permeability, porosity and flow resistance of filter media cannot be treated as constant but as functions of the pressure [5.7]. For most practical purposes it is better to measure them.

Calculations of the air flow-through are possible (although only approximate) using the concept of relative permeability of the cake and regarding air as compressible.

Dewatering by centrifuging in many aspects is similar to dewatering by filtration. Also three phases of the process can be distinguished [1.1]; namely, the "capillary flow", "capillary and film flow" and "film flow". Most water is removed during the relatively short period of capillary flow. During the film flow, i.e., the last phase of dewatering, the bridge water and other physico-mechanically water content are reduced. The residual moisture content depends mainly on this phase of the process. The drained water is replaced by air. The centrifugal field compresses particular grains to each other, reducing pores between them so that the capillary pressure becomes higher and the resistance of the material to both liquid and gas flows increases.

Dewatering by self-drainage is identical with the centrifuge dewatering, the only difference being the much longer periods of time required to achieve the equilibriums between the centrifugal (gravity) tension and capillary pressure forces. The manner by which shaking and vibrations (e.g., in a railway car or ship hold) enhance self draining of concentrates is, in general, not very well known. Moisturizing of porous media fine bulk materials should be regarded as a different process. Because of the hysteresis moisturizing requires a completely different mathematical approach [1.2]. It is more complex.

Demoisturizing in many cases can be satisfactorily described although only calculated approximately, while moisturizing has not been satisfactorily described by mathematical functions to date [1.2]. It requires different approaches and different "mathematical tools".

2.5.2 Mathematical approach

2.5.2.1 Mathematical models; their usefulness

Most mathematical theories considering the process of dewatering/moisture migration and related problems are developed to describe the inter-relation between acting forces, namely:

1. Forces which bind the liquid phase within the porous systems (e.g., adhesion, capillary, surface tension forces);
2. Forces of resistance to fluid flow;
3. External forces influencing fluids (e.g., gravity, centrifugal, pressure forces).

The practical goal of description is to create an opportunity to calculate and predict results of dewatering and to select adequate equipment without carrying out experiments. Mathematical models are also needed for process control purposes.

The capillary pressure curve is a key to understanding the physics of dewatering/moisture migration. To date this curve is drawn from experimental data only since no acceptable theory has been developed to permit it to be represented as a graph of a mathematical function. Mathematical theories which would generally and completely describe processes of dewatering/moisture migration/moisturizing of porous systems (fine bulk materials) are not available to date.

Many tentative attempts have been made to achieve this goal. In some cases, they are successful, e.g., for idealistic geometric models of porous media like packs of glass spheres etc. but they do not give satisfactory results for real fine bulk materials and real processes.

To date for all practical calculations empirical and semi empirical formulas are used. There exist many simple equations which permit description of particular elements of these processes within certain limits. They can be used for predictions of results within value ranges close to data supported by precedent experiments.

Practical engineering data have to be obtained experimentally using experimental batch- and pilot-scale equipment. The use of empirical formulas however, can diminish the required quantity of experiments.

2.5.2.2 Examples of mathematical equations and formulas describing selected features of the process of dewatering/moisture migration

In this chapter equations and formulas are analysed according to the following scheme:

- A. Identification, reference
- B. Formula
- C. Symbols
- D. Assumptions
- E. Use
- F. Restrictions

1. A. (Identification, reference) DETERMINATION OF THE RESIDUAL MOISTURE IN THE CENTRIFUGING PROCESS [1.1].

- B. (Formulas) General (start point) equations

$$W = W_i + W_a + \frac{H-hs}{H} (W_z + W_h) + \frac{hs}{H} W_{kst}$$

(after equilibrium is established)

$$W_z + W_h = \left[K_1 \frac{O_k \rho_k}{z d_m} \right]^b ; K_1 = \frac{\sigma \cos \theta}{\rho_{FL} g}$$

$$h_s = a_1 \frac{\sigma \cos \theta}{\rho_{FL} g z} \left[\frac{O_k}{d_m^2 \epsilon} \right]^{1/3}$$

C. (Symbols)

W	residual moisture
W _i	internal liquid (inside pores) [mass, %]
W _a	adsorption liquid [mass, %]
W _i + W _a	rigid water [mass, %]
H	height of cake [m]
h _s	capillary head [m]
O	specific surface [m ² /kg]
O _k	idealistic specific surface [m ² /kg] (equivalent spheres)
W _z	bridge moisture [mass, %]
W _h	physico-mechanically bound moisture [mass, %]
W _z + W _h	moisture which is drained by the film-flow. [mass, %]
W _{kst}	capillary moisture [mass, %]
K ₁	constant value
σ	surface tension [J/m ²]
θ	wetting angle
ρ _{FL}	density of liquid [kg/m ³]
ρ _k	density of solid grains [kg/m ³]
g	gravity acceleration [m/s ²]
z	acceleration number (z = ω ² /g)
d _m	arithmetic mean grain size

- e pore number
- b exponent, determined experimentally
- a_i constant value

D. (Assumptions)

- a) The wetting angle θ is constant.
- b) The size distribution is expressed by the arithmetic mean size d_m .
- c) The specific surface O_k is not a real one but calculated for equidimensional spheres.
- d) The calculation is done only for the equilibrium state after the process of dewatering is already complete.
- e) The material is considered as incompressible.

E. (Use)

The equations permit one to see trends. They can be considered as a qualitative but not a quantitative description. They may help to plan experiments.

F. (Restrictions)

These equations are half empirical. Constants a and b have to be determined by experiments. They are valid only within a range determined by experiments.

2. A. RESIDUAL MOISTURE, SATURATION DEGREE, CAPILLARY PRESSURE, INITIAL PRESSURE (NEEDED TO START THE DEWATERING PROCESS). Simple formulas [1.2], [5.1] ready for calculations.

B.(a) Residual moisture (centrifugal dewatering)

$$S_{Rf} = K_{\infty} \left(\frac{\gamma_L}{g \Delta \rho Z_m B} \right)^P$$

Author: Bender [1.2]

(b) Saturation degree (filtering)

$$S_{Rg} = K(H) \left(\frac{H \gamma_L \cos \delta}{B \Delta p_g} \right)^{0.264} \quad \text{Author: Brownel, Katz}$$

(c) Capillary pressure in cylinder-shape capillaries

$$\alpha) p_K^0 = g(\rho_L - \rho_g)h = \frac{2\gamma_L}{r} (\cos \delta) f(B_0, \delta)$$

Author: Padday [1.2]

$$\text{where } B_0 = g(\rho_L - \rho_g) \frac{d^2}{\gamma_L} \quad (\text{Bond number})$$

For sufficient small capillary radii ($r = d/2$)

$$\beta) p_K = p_K^0 = g(\rho_L - \rho_g)h = \frac{2\gamma_L}{r} \cos \delta$$

(In this case the minimum is approximated by a sphere)

d) Initial threshold pressure (as needed for starting the dewatering process)

$$\alpha) p_e = C \frac{1 - \epsilon}{\epsilon} \frac{\gamma_L \cos \delta_{re}}{\bar{X}_{1.2}} \quad \text{Author: Schubert [1.2]}$$

$$\beta) p_e = 4.6 \frac{1 - \epsilon}{\epsilon} \frac{\sigma}{\bar{X}} \quad \text{Author: Wakeman [5.1]}$$

C.

S_{RF}	residual moisture after centrifuging
γ_L	surface tension of the liquid
g	gravity acceleration
$\Delta \rho$	difference of liquid and gas density
Z_m	mean acceleration number
B	permeability
$K_{\infty, P}$	material parameters depending on the porosity, particle size distribution and wettability to be determined experimentally
S_{Rg}	residual moisture after filtering (with flow-through of gas) with the pressure difference Δp_g
H	height of the cake (dewatered bed) for $H < 50 \text{ mm}$ $\kappa = 0.025$, for $H > 750 \text{ mm}$ $\kappa = 0.012$
κ	value depending on the height H
B	permeability of material saturated with liquid
δ	effective wetting angle
Δp_g	difference of pressure of the gas flowing through the dewatered bed
p^0_k	capillary pressure in the axis of the capillary tube
ρ_L	density of liquid
ρ_g	density of gas
$r = \frac{d}{2}$	radius of the capillary tube
B_0	bond number; $f(B_0, \delta)$ function given in tables [1.2]
p_k	$p_g - p_L$ capillary pressure
p_e	initial pressure required for starting the filtration/dewatering
C	constant value depending mainly on particle shape

- $X_{1,2}$ mean particle size of a particle size distribution; it is inversely proportional to the specific surface area
- ϵ porosity, ratio of pore volume to the whole volume of media
- δ_{re} effective retreat wetting angle
- σ surface tension [N/m]
- X particle diameter [m]

- D.(a) Constant capillary head h_k instead of a capillary pressure distribution.
- (b) Empirical only.
- (c) Cylindrical capillaries in the equation b) the meniscus is represented by a sphere.
Effective wetting angle as established in an equivalent cylindrical (constant section area) capillary.
- (d) a) Establishing the retreat wetting angle is problematic. Must be established for every porous media empirically.
b) The porous media is incompressible.
- E. These equations permit one to see trends and can serve for calculations for specific purposes in restricted conditions.
- F. With the exception of the equation C, β) widely used for measuring the surface tension these formulas, being purely or at least half empirical can be used only in specific limited conditions, similar to those in which experiments serving to establish them have been carried out.
Equation (a) does not apply to dewatering by gas under pressure flowing through

A. SATURATION DEGREE DEPENDING ON TIME[1.2]
(centrifuging)

$$B. S = a \left[\frac{B_{pL} r_a w^2 t}{\eta_L (r_a - r_i)} \right]^b \quad \text{Author: Bender}$$

- C. S_t saturation degree
 B permeability of full saturated media
 ρ_L density of the liquid
 r_a extend radius of the porous system in
 a centrifuge
 θ angular speed
 t time
 η_L viscosity of the liquid
 $r_a - r_i$ height of the porous bed (cake)
 a, b constant values which have to be
 determined experimentally, e.g., for
 plastic (acrylic) spheres with the
 diameter $20 \mu m \leq x \leq 50 \mu m$ $a = 0.26$, $b =$
 $-2/3$ (Bender)

D. The porous system is homogenous, isotropic and incompressible. The influence of gravity is omitted. Constants have to be determined empirically.

E. Foreseeing of the kinetics of the dewatering process.

F. The use is restricted to the same material and the same conditions for which a and b were determined.

A. THICKNESS OF CAKE DURING THE ROTARY FILTRATION [5.4].

$$B. h_k = \frac{2}{\eta R_c} \sqrt{k} \sqrt{\Delta p} \sqrt{\frac{\alpha_1}{360}} \sqrt{\frac{1}{n}}$$

$$k = \frac{dVL}{dh_k/A} = \frac{F_v}{(1-\epsilon)(100-F_v)-\epsilon F_v}$$

C. η liquid viscosity [N/sec.m²]

R_c resistance of the porous system [m⁻²]

k parameter of concentration

Δp pressure difference [bar]

α_1 cake formation angle - equivalent to a constant filter immersion depth [°]

n filter speed [min⁻²]

D. The law of Darcy is valid; the cloth resistance negligible.

E. Used for comparing the capacity of filters for given materials.

F. Has to be supported by experimental data.

A. DARCY'S LAW [1.11].

$$B. Q = -KA (h_2 - h_1)/h \text{ or}$$

$$Q = -K'A (p_2 - p_1 + \rho gh)/h$$

(From these simple forms which are equivalent expressions of Darcy's experiment carried out in 1853 have been developed several forms of differential equations for different characteristics of materials and different conditions of experiments [1.11]).

- C. Q Volume of fluid percolating in unit time.
 K, K^1 constants depending on the properties of
 fluids and the porous medium.
 $h_2 - h_1$ height of sample (porous bed)
 h hydraulic head
 A section area of the porous bed
 $p_2 - p_1$ pressure difference at the upper and lower
 boundary
 ρ density of the liquid
 g gravity acceleration
- D. Porous media is isotropic, homogenous and incompressible.
- E. Most equations and formulas developed for description of the dewatering/moisture migration/moisturizing processes are based on assumption that Darcy's law is valid.
- F. Darcy's law is not valid at very low and very high velocities.

2.6 Sequestering Water

The Mont Wright iron ore concentrate is composed of relatively large size grains and probably is only moderately hydrophilic. This is the reason for the self dewatering phenomenon. Making this concentrate more hydrophobic and decreasing the surface tensions of water contained there would result in decreasing the residual moisture during dewatering. Rendering the concentrate more hydrophilic would thicken the layers of physico-chemically bound (rigid) water and therefore diminish the water migration effect.

Assuming that 10 to 15 per cent of water contained in the concentrate (having about 4.5% of moisture by weight) is "rigid" water one can foresee that even increasing the rigid water volume twice would not radically prevent self draining.

If a surfactant should be used for this purpose it would have to be added after filtration. Naturally thorough mixing with the concentrate would have to be done in order to make it as effective as possible. Technically it would not be easy.

A technically achievable and effective water sequestering may consist in adding to the concentrate a solid substance known for its water adsorption/retention characteristics. To the group of such substances belong bentonite which usually can absorb five times more water than its weight [7.5] and peat moss which can retain up to nine times more than its weight [7.2]. In both cases a large part of water is bound physico-chemically so that centrifuging without any chemical treatment would not dewater these materials effectively.

The water retention characteristics of both bentonite and peat moss can often be improved by adequate chemical treatment. There are many different types of bentonites. By addition of suitable sodium salts most of them would show an increase of swelling (and therefore probably an increase in water retention) capacities [7.3], [7.5], [8.2].

A considerable part of the surface of wet peat, and almost all surface of peat moss dewatered to less than 40% moisture is hydrophobic [7.1]. Adding anionic surfactants for example, sodium dodecyl sulphate (SDS) renders the peat moss hydrophilic [7.1]. This way air dried peat moss can be used instead of wet what would significantly reduce the amount needed for sequestering water.

Both bentonite and peat moss have not only water retention but also swelling and binding properties. Added to the concentrate in large amount, if enough water were present, they would tend to increase the concentrate's cohesion and to worsen its transportability. Therefore only low percentages of these substances can be used and only in such cases where the moisture content in the concentrate is relatively low.

2.7 Transportability of Fine, Wet, Bulk Materials

A fine bulk material has a low transportability when its particles tend to stick together during transport and storage, stick to walls of bins, bunkers, cars, and containers, form bridges and vaults obstructing hoppers, stick to conveyers, and making the handling difficult and costly.

There are many methods of determining the transportability [3.7]. Observing the behaviour of transported loose materials it is easy to associate the angle of repose of fine bulk materials with their transportability. Therefore, numerous investigators have tried to develop an index of transportability based on measuring the angle of repose of a given material [3.7], [3.13]. Unfortunately, the angle of repose depends on such secondary factors as particle size and the height of material pile on which it should be measured, therefore, it cannot serve this purpose.

Methods based on measurements of time for material to flow from a container through a calibrated orifice [3.7] also had very limited success.

On the basis of the direct shear test known from the soil mechanics [1.12], [1.13], [1.4] A. Jenike [3.7] developed a test which served for the design of bins and bunkers. Also ring cell shear tests [3.7] developed mainly for investigations of the rheology of loose materials can be used for determining their handability. For some materials triaxial compressive strength test can be used for this purpose. In Poland, for determining the transportability of wet fine coals containing shales and other clay material, a method of measuring the tensile strength of consolidated samples was successfully used [3.7]. It is very likely that plasticity tests used for ceramics and carried out with the Brabender Plastograph [8.8] could be used for iron ore concentrates.

If a transportability test should be adapted to checking whether or not a given surfactant or sequestering agent has a detrimental effect on the handling of iron ore concentrate the

attention should be paid first to the Brabender Plastograph tests (since this instrument is already available in CANMET). The second choice would be the measuring of tensile strength [3.7], since this method is very simple and measures factors which directly influence the handleability. The third priority should be given to the ring cell shear and/or to A. Jenike's shear method.

3. OVERVIEW OF LITERATURE; LIST OF REFERENCES WITH SHORT SUMMARIES OF FEATURES RELATED TO THE DEWATERING/MOISTURIZING/SELF DRAINING OF FINE BULK MATERIALS

SECTION 1. GENERAL KNOWLEDGE AND THEORY

1.1 W. Batel

Menge und Verhalten der Zwischenraum Flüssigkeit in Körnigen Stoffen. Quantity and Behaviour of the Interface Fluid in Fine Grain Bulk Materials. Chemie - Ing. - Techn. Vol. 33. 1961/No 8; pp. 541-547.

This is one of the most important articles for this work. Good classification of water layers is given. An equation of residual moisture distribution developed. The question of residual moisture is equivalent to the question of acting forces, namely: 1) forces binding the liquid (capillary adhesion); 2) forces of resistance to moving fluids; 3) external forces (centrifugal, pressure, gravity, etc.). Capillary head depends on speed, surface tension, pore number, size of grain, specific surface. Capillary moisture is easier to drain than bridge moisture. There are 3 phases of dewatering: Capillary flow, capillary/film flow, film flow. Residual moisture depends on capillary head.

1.2 H. Schubert

Kapillarität in porösen Festoffsystemen. Capillarity in Porous Systems of Solids; Springer-Verlag, 1982, 349 pages.

One of the most important reference items for this work. The book summarizes to a great extent all work in this area.

Capillary means the behaviour of fluids under the influence of the interface (surface) tension. A unique presentation of the capillarity for all science areas and technologies is impossible. Many approaches are necessary.

Capillary pressure curve is the key to understanding the capillarity. It gives the capillary pressure as a function of the quantity of liquid in the porous system. There are two capillary

pressure curves; 1) static, for liquids being in equilibrium and 2) dynamic (developed by the author), for relatively fast moving meniscus of liquid. In some cases when there is no equilibrium the second type must be used. Calculations with constant capillary pressure so often described in literature are inadmissible. Moisturizing and demosturizing are two different processes needing different approaches.

The lower limit of capillary values which can be defined by a microscopic manner lays at about $x = 3$ nm (diameter of drops or bubbles).

The bridges of liquid between solid particles are of highest importance. So far calculations concerning the bridge moisture are possible on idealistic geometrical models only.

All theories of this work assume that the porous media (pores system) is homogenous, isotropic and does not change (shrink or expand) during the flow. For demosturizing it is assumed that the liquid is evenly taken from all places over the porous system. Demosturizing can be satisfactorily, although only approximately calculated, while moisturizing has not been satisfactorily described by mathematical functions.

Exact measurements of wetting angle are not possible to date i.e., because of hysteresis. It depends on roughness of the surface of solid, on its shape and on adsorption properties. The wetting angle on sharp edges is deformed. Most difficult is measuring the dynamic wetting angle.

- 1.3 A.M.Al Taweel, B. Delory, J. Wozniczek, M. Stefanski, N. Andersen, H.A. Hamza
Influence of the Surface Characteristics of Coal on its Floatability; Colloids and Surfaces, 18 1986; pp. 9-18.

This work refers to adsorption characteristics of coal and to the dynamic adsorption technique (inverse gas-solid chromatography) used to evaluate surface characteristics. (Determining the surface concentration of the hydrophilic active sites versus the hydrophobic active sites may be useful in evaluating limits of residual moisture content in iron ore concentrate.)

1.4

Annual Book of ASTM Standards 1984. Section 4; Vol. 04.08; Soil and Rock; Building Stones.

In particular the following standards were considered and/or used:

- D 425-79 Test Methods for Centrifuge Moisture Equivalent of Soils.
- D 698-78 Test Method for Moisture-Density Relations of Soils and Soil Aggregate Mixtures.
- D 1557-78 Aggregate Mixtures.
- D 2168-80 Methods for Calibration of Laboratory Mechanical Rammer Soil Compactors.
- D 2216-80 Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock and Soil Aggregate Mixture.
- D 2325-68 Test Method for Capillary Moisture Relationship for Coarse and Medium Textured Soils.
- D 2434-68 Test Method for Permeability of Granular Soils.
- D 2607-69 Classification of Peats, Mosses, Humus and Related Products.
- D 2850-82 Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression.
- D 2980-71 Test Method for Volume Weights, Water-Holding Capacity and Air Capacity of Water Saturated Peat Materials.
- D 3080-72 Method for Direct Shear Test of Soils Under Consolidated Drained Conditions.
- D 3152 Capillary Moisture Relationship for Fine-Textured Soils by Pressure Membrane Apparatus.
- D 4253 Maximum Index Density of Soils Using a Vibratory Table.
- D 4254 Minimum Index Density of Soils and Calculations of Relative Density.

1.5 P.L. Zenkov

Mekhanika nasypynkh Грузов.

Mechanics of Bulk Materials; Mashinostroenie, Moscow 1964; 244 p.

This book summarizes the state of knowledge in late fifties in the area of macro description of bulk materials. Of primary concern

to this work are chapters devoted to the influence of consolidation and of the moisture content on the mechanical properties of the material. Porosity and bulk density depends on moisture content. It is very difficult to get rid of molecular layers of water. Even forces 70,000 times larger than gravity are not sufficient. The percentage of maximum capacity of molecular water adsorption for sand particles is for 1 to 0.5 mm grain size about 1.57%. Equation for calculating two types of curves of bulk density as function of moisture content are developed. Tables give percentage of molecular water as a function of particle size. It is assumed that the maximum thickness of the molecular moisture layer is 0.005 mm.

- 1.6 J.W. Tierney, B.S. Gottfried, Guan Qi Zhao
A Simulator for Dewatering of Coal Fines; University of Pittsburgh; Use of Computers in Coal Industry, 1984 (?); Chapter 26; pp. 230-236.

Equations for predicting the performance of vacuum filters and centrifuges used for coal dewatering are presented. These equations are the basis for a "dewatering module" being part of the coal preparation plant simulator developed at the University of Pittsburgh. Residual moisture, among other parameters, is calculated using a simplified Brown (1950) equation. The article is a good example of the development and use of computerized methods in the dewatering techniques.

- 1.7 J.E. Lawver, W.D. Carriere
Modeling of Phosphatic Clay Disposal Systems; Mineral and Metallurgical Processing; November 1984; pp. 198-204.

Described is the use of mathematical and physical (centrifuge) models that can be used for analysing and evaluating various systems for the consolidation (dewatering and minimizing the volume) of phosphatic clays.

Centrifuges have been used for more than 50 years to model soil behaviour. The ratio of the physical dimension of the prototype

(height of the structure of a prototype dam) to the model is equal to the acceleration rate, and the consolidation time is proportional to the square of the acceleration rate. Classic Terzaghi (1924) consolidation theory is used in most practical cases of geotechnical engineering problems. It assumes that during consolidation:

- the void ratio remains constant;
- the coefficient of permeability and compressibility remain constant;
- the self weight is neglected.

These assumptions are not sufficiently accurate for phosphatic clay, therefore, a much more general, nonlinear finite-strain consolidations theory of McNabb (1960) and Gibson (1967) was used. Computers were used to solve numerically proposed equations. Eighteen more references, useful for these kinds of problems, are given.

1.8 S. Ergun

Fluid Flow Through Packed Columns; Chemical Engineering Progress; Vol. 48, No. 2, February 1952; pp. 89-94.

The equation developed is general but experimental studies were confined to gas flow through crushed porous solids. Factors determining the energy loss (pressure drop) are:

1) rate of fluid flow; 2) viscosity and density of the fluid; 3) closeness and orientation of packing; 4) Size, shape and surface of the particles. Total energy loss in fixed beds can be treated as the sum of viscous and kinetic energy losses.

1.9 W.J. Rankin, P.W. Roller, R.J. Batterham

Analysis of the Permeability of Granulated Iron Sinter Feeds Using the Ergun Equation; Minerals and Metallurgical Processing; February 1985; pp. 53-59.

Applications of Ergun equation (see 1.8) to sintering process of granulated iron feeds is shown. A simple laboratory method of measuring permeability of air through a granulated mix is described.

1.10 P. Staszczuk, A. Waksmundzki

Własności warstewek hydratacyjnych na powierzchni ciał stałych.

Properties of Hydration Layers on the Surface of Solids;

Problemy Agrofizyki; PAN, Ossolineum, 1982 vol. 37, 81 pages.

Four types of water are distinguished: 1) volume water; 2) water bound physically and physico-mechanically; 3) water bound physico-chemically; 4) water bound chemically.

The second type still has properties of free water but depends heavily on capillary and osmotic forces binding it in capillaries of $r < 10^{-6} \text{ m}$. The third type is adsorbed as mono and poly-molecular layers. Binding forces here are about 10 times smaller than within type 4. Types 3 and 4 water have different physical properties from those of free water.

The presence of a concave meniscus in a capillary and the decrease of pressure of water steam above it is not a cause but a result of capillary raising (lifting) of water. The driving force of the capillary lifting of water is a self diffusion of more free water molecules in a thicker layer to more bound water in a thinner layer where their mobility is lower. The binding forces are stronger and the mobility lower, closer to the solid surface.

1.11 A.E. Scheidegger

The Physics of Flow Through Porous Media; University of Toronto Press, 1957; 353 p.

This is a monography of physical theories connected with flow of fluids through porous media, mainly in a state of saturation (but not exclusively). Definitions based on mathematics for describing porous media are given. Darcy's law is largely discussed. The theories are directed towards resolving problems of oil exploitation, its flow through mineral beds, displacing with water, etc. In many cases theories are checked empirically, not in real processes but on physical models. Considerations of capillarity are based on the notion of contact angle and interface tension (surface tension). Theories described are qualitatively correct. They are based, however, on simplified assumptions. Adsorption theories of Gibbs and

Polanyi, BET (Brunauer, Emmett and Teller) and others are summarized. Capillary pressure curve and limitations of capillary pressure concept are discussed. Phenomenon of hysteresis is stressed. Chapter "Hydrostatics in Porous Media" is particularly useful.

1.12 K. Terzaghi, R.B. Peck

Soil Mechanics in Engineering Practice; John Wiley & Sons, N.Y., 1967; p. 729.

Terzaghi was the main creator of Soil Mechanics as a technico-scientific discipline. Several of his definitions, theories and approaches have been universally accepted. Concepts developed in chapters devoted to the physical properties of soils, like index properties and hydraulic and mechanical properties including permeability, compressibility, consolidation properties, effects of vibration and drainage of soils are very useful for considerations relative to dewatering of porous media like concentrates. The same concerns the chapter on "Theoretical Soil Mechanics" including hydraulics of soils, etc.

1.13 T. Jeske, T. Przedeki, B. Rossinski

Mechanika Gruntow; Soil Mechanics; PWN Warszawa 1966; p. 431.

Very clear presentation of soil mechanics. Principal components of soil, structure and texture, classification, phenomenon of thixotropy, physical and mechanical properties, water movement in soil described. Laboratory technics of determination of basic properties presented.

1.14 J. Laskowski

Chemia fizyczna W procesach mechanicznej przerobki kopalin.
Physical Chemistry in Mineral Processing; Slask, Katowice 1969; p. 262.

Surface phenomena are described including surface tension, wettability, adsorption. Physico-chemical principles of flocculation and flotation presented. Influence of zeta potential on mineral processing processes discussed.

1.15

Fineness of Portland Cement by Air Permeability Apparatus; ANSI/ASTM C 204079; Annual Book of ASTM Standards; Part 13.

The Blaine method of measuring the specific surface area which may be used for iron ore concentrate is described.

1.16 J. Wozniczek, A.M. AL Taweel

Influence of Pore Structure on the Beneficiation and Utilization of Eastern Canadian Coals.

Report by T.U.N.S. for A.R.L. - National Research Council of Canada, ARL Technical Report 51 NRCC23813, 1984.

This report give a very pertinent discussion on surface properties of mineral matters. The overall "wettability" (of coal) depends on the balance between the hydrophobic and hydrophilic active sites. The ratio of lyphilic and hydrophilic active sites is an important parameter which characterises the surface properties, for example the floatability of coal.

1.17 E.G. Kelly, D.J. Spottiswood

Introduction to Mineral Processing; John Wiley & Sons, New York, 1982, pp. 491

This is a modern manual in which problems relative to characteristics of fine bulk material and to techniques of dewatering are described.

SECTION 2. REFERENCES CONCERNING IRON ORE IN PARTICULAR

2.1 W. Stahl, R. Bott, H. Anlauf

Druck filtration von Eisenerztruben.

Pressure Filtration of Iron Ore Slurries;

Aufbereitungs-Technik. Vol. 24, 1983; Heft 5, pp. 243-251

Cake formation rate and its thickness are given by simplified equations derived from Darcy's law. To further diminish the residual moisture in cake the superposition of the vacuum filtration with over-pressure (hyperbar vacuum filtration) can be used. The best results were obtained when the difference of pressure of the over-pressure was slightly higher than that of the vacuum. In the case of fine iron ores when the vacuum was 0.8 bar the optimum overpressure was 1 bar. The residual moisture was reduced then from over 10% to 7.5%.

2.2 K.V.S. Sastry, D.J. Kawulok - Englund, C. Hosten

Comparative Study of the Vacuums Filtration Behaviour of Iron Ore Concentrate Slurries; Mining Engineering, Oct. 1983; pp. 1432.

Authors indicate that there are few research reports on the dewatering of iron ore concentrate slurries. "There is a need to understand the principles and mechanisms involved in the filtration of iron ore concentrate with a goal of developing more efficient filtration techniques." Investigated were fine concentrates (45 to 98% -400 mesh). Decreasing the pH generally increased the capacity of filters and sometimes lowered the cake moisture. Flocculant addition (cationic Catfloc LV) at a rate of 0.15 g/kg did not substantially change the moisture content, but increased the filter capacity.

2.3 A.K. Deysarkar, G.A. Turner

The Effect of Vibrations on the Flow Properties of a Saturated Paste of Iron Ore and Water; International Journal of Mining Processing; 6 1980; pp. 257-276.

A flotation concentrate (Knob Lake) ground to 62% minus 325 mesh was used, with water content of 16% w/w. Vibration frequency of 10 Hz, and 0.254 mm peak to peak amplitude decreased the yield stress from 20 kPa in the unvibrated state to almost 0 and the viscosity was reduced markedly. Only the saturated type of structured mass can be liquified (yield stress and viscosity reduced) by vibration. In the pendular state both shear and dilatational waves cause distortion of the pendular bonds which, by virtue of the change of curvature of the liquid surface of the water blobs, alters the normal particle-to-particle force. The wave does not suffer much attenuation in this state. Viscosity and the nature of boundaries of the paste material has little effect. Investigations were confined to mainly pastes in saturated state. Equations for determining the value of the yield stress and viscous material parameters are given. Funicular and pendular states involve a completely different structure with different behaviour, as compared to the saturated state.

2.4 D.T. Vachon, W.H. Moores, R. Zalloum, W.H. Cameron

The Characteristics of Iron Ore Mill Effluents and Laboratory Investigation Into Their Treatability; Report prepared for Iron Ore Processors Task Force, 1981.

Investigating the removal of colloidal solids from iron ore processes waste water by sedimentation was the main goal of the study. Interaction of coagulants and flocculation aids was studied, and several dosages examined. Costs of use calculated. Influence of a few different surfactants was studied.

2.5 W. Petruk

Evaluation of a Middling Cleaner Tailings From the Mount Wright Concentrator by Image Analysis Studies; Division Report MSL 84-167 (IR); CANMET, Energy, Mines and Resources Canada; 1984.

The middling cleaner tailings from Mount Wright Concentrator were analysed with the set of instruments [Scanning Electron Microscope (SEM) X-ray Analyser (EDXA) and Image Analyser (SEM-IPS)]. Hematite, goethite, quartz, biotite, amphibole, and apatite were identified. The

circularity factor of free hematite grains in the -200 mesh fraction was determined. Most of the free hematite grain in this fraction were pseudorectangular with the largest ones being elongated.

2.6 F.E. Hanes

Investigation of an Iron Ore Concentrate from Wabush Mines Canada; Department of Energy, Mines and Resources, Mines Branch, Ottawa; Mineral Processing Division, Oct. 1970; Test Report MPT-70-18.

Angles of repose and flow-moisture points were established for two different samples of Wabush Mines concentrate. Relation between angle of repose and moisture content was checked for 4 moistures. Flow-moisture point was established at 7.75 and 7.92% moisture. Cut-and-dried sharp determinations of flow moisture points could not be done because of particle shape described as platey-shape characteristic for specular hematite.

2.7 Ch. Côté, M. Tremblay

Unpublished Information, 1986-1987; Québec Cartier Mines, Mount Wright.

Basic information about functioning of the concentrator, dewatering and water migration, analyses performed, grades, production and economy.

2.8 Québec Cartier Mines

Results of Investigations on Filter Aids Carried Out by ALCHEM Inc., CALGON and Q.C.M. Engineering and Process Development; Québec Cartier Mines; Test Work Reports, 1978, 1979, 1980.

Results obtained on laboratory scale showed that it was possible to obtain moisture reduction up to 2.5-2.9% using chemicals and different filter media.

2.9 L.F. Dolina

Effectivnoe poverkhnostno-aktivnye veshchestva dlya snizheniya vlazhnosti tonkoizmelchennikh zhelezorudnikh koncentratov.

Effective Surfactants for Decreasing the Moisture of Fine Iron Ore Concentrates.

Obogatimost zheleznikh rud Maryupolskogo mestorozhdeniya No. 2. 1971.

Results of tests on 25 different surfactants used as filter aids are presented. All of them decrease the surface tensions of water from 72-74 erg/cm² to 24-50 erg/cm². There is, however, no simple dependence between decreasing surface tension of water and residual moisture content of iron ore concentrate after filtration. Filter aids should be added in dilute form and in many points of the pulp flow so that they will be very evenly distributed.

SECTION 3. TRANSPORT AND STORAGE

3.1 P.G. Kihlstedt

Consistency of Concentrates; Royal Institute of Technology, Stockholm
Tenth International Mineral Processing Congress; London, 2-14, April
1973; pp. 1-15

This is a fundamental article on behaviour of concentrates and other ground mineral materials in mineral processing, and in particular during the transport and handling, depending on their moisture content and compaction. Relationships between shear strength and pore number, pore number and moisture number under different conditions were investigated and discussed. Different states connected with increasing moisture content have been studied and discussed.

Three water layers are distinguished: rigid water (layers of about $0.2 \mu\text{m}$ thickness or less), capillary water and free water. The following states of material are described: dry, pendular (up to about 20% moisture by volume, looser compaction, particles bound stronger), funicular (free liquid water partly fills the pores, compaction again denser), capillary (pores completely filled with water, possible air bubbles but no excess pressure in pores), supersaturated (particle loose contact and support from one another). Most organic additives can influence the relationship curve between moisture number and pore number but the pore number - shear strength curve is not affected. Water repellent flotation reagents influence both the compaction properties and the cohesion/friction properties. Flotation concentrate have a lower shear strength and higher fluidity index.

3.2 B. Fagerberg

Hazards of Shipping Granular Ore Concentrates. Part 1; Canadian Mining Journal, July 1985; pp. 53-57.

Wrecked ore concentrate carriers are listed, type of cargo and causes of wreckage analysed. Definition of effective pressure, and pore pressure given, consolidation model after Terzaghi [1.12]

described. The mechanics of cargo shifting discussed. A program for establishing a method for determining the critical water content is presented.

3.3 B. Fagerberg

Hazards of Shipping Granular Ore Concentrates. Part 2; Canadian Mining Journal, Aug 1985; pp. 81-86.

Investigations show that no disturbing water segregation phenomena would occur in concentrate cargos below the upper critical water content. The compaction tests with Proctor apparatus serve to determine the upper critical water content. All compaction curves (relationship of moisture content versus void ratio) have about the same general shape. The upper critical water content of a uniform wet concentrate is indicated by the moisture at optimum compaction according to Proctor method, that means by the minimum point at the compaction curve. Relationships between upper critical water content and grain size is shown and discussed. Comparisons between Proctor methods and other test procedures for determination of upper critical water content are described. All methods other than Proctor including the Canadian flow moisture point determined on a flow table are applied under uncontrolled conditions. The degree of compaction of materials used is unknown and probably does not correspond to the compaction attained in a concentrate cargo at sea.

3.4

Proctor Method for Determination of Safe Water Content of Granular Ore Concentrates Carried in Cargo Vessels; Summary of a Swedish Article: The Influence of the Water Content at Shipment of Granular Ore Concentrates; Jernkontorets Annaler, Vol. 146, Stockholm, 1962.

Short and clear description of Proctor method. Conditions which may cause shifting of concentrate cargo are discussed. This shifting may occur only if the permeability of the concentrate is low, i.e., if it is fine grained. Excess pore pressure may be momentarily created,

smallest grains loose proper contact with each other and as consequence internal friction and cohesion forces as well as shearing strength disappear. First, the bottom layers and then the concentrate layers higher up loose their stability.

3.5 N.W. Kirshenbaum

Transport and Handling of Sulphide Concentrates: Problems and Possible Improvements; Technomic Publ. Co. Inc., Stanford Conn., 1968.

Several cases of concentrate shifting described. Comparison of results from different methods of measuring critical moisture contents in concentrates are given. This book refers not only to shifting problems and methods of preventing them but also to several other problems connected with the transport of concentrates. Common preventive methods and regulations are discussed.

3.6 F. Guerra

The Transportable Moisture Limit for the Transportation of Ore Concentrates in Vessels; Vancouver Symposium, 1970(?).

The use of Flow Moisture Point Test as recommended by the Canadian Bulk Cargoes Code for determining the upper safe limit of moisture is criticised. It does not reflect any physically based characteristic of the material. It does not show whether in different tests the same compactive energy was used, nor does it relate to the influence of density or moisture saturation on the results of the test. Compaction curves are shown as function of moisture content based on total weight rather than on volume percentage. A moisture-density-saturation method could also serve to select transportable moisture limits. Cohesionless materials with relative densities greater than 50% are probably immune to the dangers of "liquefaction" regardless of their degree of saturation. The limiting degree of saturation would then be about 75% for all concentrates. A sample that is at the optimum moisture content has nearly as large a degree of saturation as can be reached by compaction. No amount of pounding can cause an appreciably larger degree of saturation.

3.7 M. (Maria) Stefanski

Zdolnosc transportowa drobnouziarnionych wilgotnych wegli
Transportability of Fine Wet Coals. G.I.G. thesis, 1974, Katowice

Ten different methods of measuring rheological characteristics and in particular the flow of fine bulk material have been tested and discussed. None of them proved to be adequate for measuring the transportability of fine wet coal having relatively high content of clay minerals. An original method of measuring the tensile strength of mould and consolidated (in standard conditions) material, was developed. The obtained tensile strength is considered as index S of transportability. The described method is basically empirical, nevertheless, many elements were theoretically justified.

3.9 N. Eaton

Moisture Migration on Carol Concentrate; Unpublished Report; Materials for a Meeting to Discuss Shipping of Iron Ore Concentrates from I.O.C. and Q.C.M. March 11, 1969.

Data on moisture migration on Carol concentrate are given. Concentrate of two vessels "Dynamic" and "Oswego Reliance" here sampled after their arrival at Philadelphia. Samples were taken from different depths of ship holds, every 5 feet. At the surface of the "Dynamic" average moisture was 0.73% while at the bottom 9.57%. At the surface of the "Oswego" about 1.7% while at the bottom 10 to 29%.

3.10 B. Fagerberg, A. Stavang

Determination of Critical Moisture Contents in Ore Concentrates Carried in Cargo Vessels; Vancouver Symposium, 1970.

Conditions at which shifting of vessel cargo's may occur are described. Proctor tests and apparatus described. Compaction curves defined, described and compared for many different materials. Flow table method and Norwegian vibration methods are criticised, and compared with Proctor method.

- 3.11 F.E. Hanes, N. Eaton, W.K. Coombes, J.L. MacAngus et al.
Report of a Meeting to Discuss Shipping of Iron Ore Concentrates from Iron Ore Company (IOC) and Québec Cartier Mines (QCM), (Water migration problems); Ottawa, March 1969.

Since the Flow Moisture Test, as recommended by the Canadian Bulk Cargoes Code, does not give adequate results for all materials (e.g., it cannot be applied to coarse grain concentrates) attempts were made to introduce size factor as an additional characteristic. The angle of repose was also studied as a possible flow test parameter.

- 3.12

The Flow Moisture Point Determination for Concentrates and Similar Materials; (Intergovernmental Maritime Co-ordinative Organization); Canadian Report discussing the Canadian Bulk Cargoes Code IMCO (Intergovernmental Maritime Co-ordinative Organization) Material for the 6th Session of the Sub-Committee on Bulk Cargoes, 1967.

A detailed description of carrying out the Flow Moisture Point Tests as recommended by the Canadian Concentrates Code is given. Differences between this procedure and that adopted by the IMCO Code of Safe Practice are discussed. Extracts from both CCC and IMCO C of SP show these differences.

- 3.13 G. Wilson

Report on Results of Tests to Determine Angles of Repose for Various Ore Concentrates For Depart. of Transport; Depart. of Public Works, Testing Lab., Ottawa; Jan. 1968.

Thirty-three different concentrates have been tested and their angles of repose listed at given moisture content. The author indicates the inaccuracy of measurements due to characteristics of material and conditions of measurement. He expresses doubts whether or not the angle of repose should really be considered as a stable and consistant characteristic of any material.

- 3.14 A. Kvalheim, E. Evensen, A. Bremseth
Safe Practice for Bulk Cargoes. An Investigation of the Flow Table Method for the Determination of Safe Moisture Limits; Geological Survey of Norway, Chemistry Div., Thronheim, Nov. 1971.

The Flow Moisture Test as recommended by IMCO (Intergovernmental Maritime Co-ordinative Organization) is examined in detail in particular as concerns reproducibility and energy of tamping. An original Norwegian vibration method is described and compared to the Flow Moisture Test.

- 3.15 J.G. Norwall, I.A. Marshall, G.S. Haslam
Carriage of Slurry; National Coal Board, North-Eastern Division, Scientific Dept., Nov. 1961.

Thirteen coal-water slurries have been examined. A novel apparatus called "vibration viscometer" was designed. It measured the flow of material of different moisture content through a 1/4" diameter hole from a cylinder vibrated on a laboratory vibration table. The "Critical free moisture point" is reached at moisture content at which the slurry stops flowing.

Authors assume that at moisture contents below this point slurries can be safely transported in ships. Possible "side effects" of long vibration, frequency and amplitude, clay content are discussed. Range of critical free moisture of different coal slurries was 18.5 to 29%.

- 3.16
Copper Ore Concentrates Aboard the M.V. Erwin Schroeder;
National Research Council of Canada; Special Report No. 162, Jan. 1963.

This report contains information concerning difficulties encountered at sea through the shifting of a cargo of copper ore concentrate aboard the M.V. Erwin Schroeder. Distribution of water contents measured two days after the ship arrived at the port showed that at the bottom of holds moisture content was 1 to 1.5% higher than on the top (14 to 16% versus 12.5-14.5%).

3.17

Canadian Concentrates Code; Marine Regulation Branch Dept. of Transport, Canada.

Most articles of this literature review, concerning shifting of concentrates during shipment and measures taken to prevent it, refer to this document. It contains definitions and descriptions of Flow Moisture Test procedure.

3.18 H.M. Woodroffe

The Problem of Shifting Metal Concentrates in Ocean Transport; Unpublished Report, December 1962.

This report summarises Canadian experience and knowledge about shifting concentrates. It recommends establishment of a meaningful criterion to control this problem. Brabender plastograph was used to characterize concentrate and the results compared with the Flow Moisture Point. Results obtained with the NCB Vibration Viscometer were also compared with the Flow Moisture Point Test results.

3.19 F. Guerra (?)

The Flow Moisture Point and its Applications to the Shipment of Concentrates; Unpublished material, 1967-1970.

Relationship between moisture content, density and degree of saturation in cohesionless material are discussed. Data relate to two different cargoes: coarse-textured, free draining iron concentrate with a low moisture content, and fine-textured, relatively impermeable copper concentrate with a high moisture content. Vibrations have a pronounced effect on the density therefore the relationship between moisture content and density is relevant to the problem. As a reference the degree of saturation is more practical than a moisture content, especially if the latter is expressed by weight. Results of the Flow Moisture Test are plotted on a relative density graph (ASTM D4253, D4254). Cohesionless materials with relative densities greater than 50% are probably immune to the danger of liquefaction regardless

of their degree of saturation. The height to which the water table can rise was calculated. Moisture content of drained concentrate from Carol Concentrator (residual moisture) was assumed to be constant at 2.6% moisture (the loaded material was 5.2%). Flow Moisture Test satisfied safety requirements and can be used when little information is available about the physical properties of the concentrate. When adequate information is available a more rational approach to testing is advisable, like the selection of transportable moisture limits as described here.

3.20 D.A. Bird, P. Cammack, J.C. Sproson

Coal Handlability and the Design of Storage Bunkers for Caking Smalls and Power Station Blends; 7th International Coal Preparation Congress; Paper C3, Australia, 1976.

The use of ring shear cell for determining the handlability of wet fine coals is described.

SECTION 4. CENTRIFUGING

4.1 O.R. Lyons

An Approximate Method of Predicting and Comparing Expected Results When Dewatering Coal by Centrifuges; Transactions AIME, May 1951; Mining Engineering; pp. 417-425.

Accepting some simplifying assumptions as to a straight line relationship between the size of product and surface moisture content of the centrifuge product as well as between average size of dewatered cake solids and composite cake plus effluent solids, a simple method of comparing different types of centrifuges is developed. Arithmetic mean is used for calculating the average size of particles.

4.2 O.L. Bruk

An Integral Mean Method of Computing the Separation Parameters of Suspensions in Filter Centrifuges; Koks, Khimiya, No. 3, 1983, pp. 12-13.

A batch-process centrifuge was used, the design of which permits collection of samples of the filtrate at frequent intervals. The period of separation of the suspension may be divided into three steps. For every step the rate of the process-kinetics of both cake and filtrate as well as the speed, acceleration, hydrodynamic head and filtration medium resistance were investigated. The very often used hypothesis that the cake is incompressible and the head and resistance are constant as well as simple averaging them - is inadmissible. Equations are derived permitting the calculation of the parameters of centrifugal separation of suspensions. Capacity, structural parameters of the rotor or resistance of the medium can be calculated when the integral mean coefficient I (which depends on the centrifugal field) and the equivalent mean resistance of the filtering medium are determined on an experimental centrifuge.

4.3 U. Breuer

Kupferkonzentratentwässerung auf Schälzentrifugen mit Rotationssiphon.
Dewatering of Copper Concentrates in Peeling Centrifuges with Rotary
Siphon; Aufbereitungs-Technik 1982(?).

Possibility of using for dewatering copper concentrates semi continuously operating filter centrifuges which have been successfully tested for chemical processes is discussed. Simple method of calculating the pressure behind the filter medium is shown.

4.4 K. Richards

The Treatment and Disposal of Coal Flotation Tailings; Mine & Quarry,
April 1986.

Cost comparison is given between filter-presses, multi-roller pressure filters and solid bowl centrifuges. The less expensive proved to be bowl centrifuges. After centrifuging tailings are mixed with cement at the rate of 1.75% and a stiff clay-like structure is attained after 29 hours curing.

SECTION 5. FILTRATION

5.1 R.J. Wakeman

The Performance of Filtration Post-Treatment Processes.

1. The Prediction and Calculation of Cake Dewatering Characteristics. Filtration and Separation; Dec./Nov. 1979; pp. 655-658 and 669.

The author improves and develops a simple mathematical model (for incompressible filter and centrifuge cakes only) which can serve to calculate the irreducible saturation level (residual moisture) in filtered and centrifuged cakes. Mean grain size as used in the model can be calculated from the specific cake resistance, cake porosity and filtrate density. A mathematical model of kinetics is developed on the basis of Darcy's law. All theoretical considerations are illustrated by practical implementing - calculations carried out on real numerical data. During dewatering two immiscible fluids - air and residual filtrate - coexist in the cake voids, and the flow mechanism of one is not only affected by the voids structure but also by the flow characteristics of the second fluid.

5.2 B. Anlauf, R. Bott, W. Stahl

Über die Druck filtration schwierig zu entwässernder Erzkonzentrate. About Pressure Filtration of Difficult-to-Dewater Ore Concentrates. Statusbericht 1984.

Vorträge zum Statusseminar 4-6 Juni in Bad Neuenahr; p. 640-650.

Vacuum filtration possibilities are approaching their limits when: 1) concentrates are too fine, 2) vapour pressure is high (e.g., in higher temperatures) or 3) when the atmospheric pressure is low due to the high altitude. Continuous pressure or vacuum-pressure filtration has more potential and will likely be used more often in the future. Extensive filtration tests were carried out investigating influences of pressure gradient, filter media, size distribution and differences of filtered ores on results of dewatering. Described were porosity, specific permeability and rate of cake formation.

Anticipation of the cake porosity by calculation is not possible. Porosity influences permeability, which decreases when compaction rises. The only reliable way is measuring. The filter media resistance to flow may be expressed by equivalent cake height. Capillary pressure distribution was experimentally determined for every case individually because the distribution of porosity, surface properties and wettability are difficult to determine. In order to predict results of dewatering one has to determine to what extent can the material be regarded as incompressible. Also the relationship between pressure gradient, permeability, porosity and filter media resistance has to be evaluated. Usually the residual moisture reached by the time the first air break through is achieved is not sufficient. Further dewatering during air flow through the cake is necessary.

5.3 W. Stahl, H. Anlauf, R. Bott

Entwässerung von Erzkonzentraten-Wege zur weiteren Restfeuchte Verminderung.

Dewatering of Ore Concentrates - Ways for Further Decrease of Residual Moisture.

Erzmetall 36 (1983) No 6, pp. 266-270.

The theory of the process of dewatering by sucking or blowing air through the filter-cake is not satisfactory. All up-to-date models are based on so many simplifying and idealistic assumptions that a prediction of dewatering results of real filtration products are unsatisfactory. Research described in this article is based exclusively on testing real concentrates in real conditions similar to those encountered in industrial practice. The residual moisture decreases at the beginning of the filtering cycle very steeply and later its kinetic curves becomes flat approaching an asymptote. Empirical equations were developed for calculations of gas flow and residual moisture. The relationship between the volume of gas used and the relative gas content (residual moisture) is exponential. Two parts of the filtering process are distinguished: 1) piston flow, 2) dewatering by air flow. The higher the pressure difference the shorter

the time needed to reach a given residual moisture. This shows the limit of vacuum filtration, and indicates possibilities for pressure or vacuum-pressure process. Problems of transferring results from batch to continuous filtration are described.

5.4 R. Bott, H. Anlauf, W. Stahl

Kontinuierliche Druckfiltration feinstkörniger Kohlenkonzentrate.
Continuous Pressure Filtration of Very Fine Coal Concentrates.
Aufbereitungs - Technik No. 5/May 1984; pp. 245-258.

The capillary pressure that has to be overcome when the filtration should start (the break through pressure) is about 0.3 to 0.5 bar for many iron, zinc, copper concentrates and for coal. Vacuum filters work at 0.8 bar. This small difference 0.5-0.3 bar is not sufficient to lower the residual moisture of fine materials, especially at short times of filtration as available in industrial practice. Higher pressure i.e., pressure or hyperbar-filtration, has to be used.

The article shows results of tests carried out on pilot scale pressure filtration equipment. For calculation of the thickness of the cake Darcy's law was used. At the beginning of the filtration cycle a "piston" water flow is assumed to occur. A capillary pressure diagram is used to explain the process. Comparisons of many parameters and efficiency of vacuum, pressure and hyperbar filtration are made.

5.5 R. Kern, W. Stahl

The Discharge of Filter Cakes. Solids/Liquids Separation Practice and the Influence of New Technologies; Dept. of Chem. Eng.; University of Leeds; April 1984; pp. 2-5.

The force of adhesion of filter cake to the filter media influences the economy of filtration. The article gives a method of measuring the average adhesion force which is an important asset for the designer. Theoretical background for adhesion is discussed and several references indicated. The liquid-bridges forces binding particles are about four times as large as the van der Waals forces, which are by an order of

magnitude greater than electrostatic adhesion forces between conductors, due to contact-potential, and these are again about 100 to 10 times as great as adhesion forces due to maximum surplus charges of opposite sign. The tensile strength for moist agglomerates with less than 30% of the void spaces filled with liquid can be calculated from the equation given by Rumpf. A centrifuge served to measure the adhesion of cake to filter media since the force is easily measured from the centrifuge speed and radius. Adhesion force depends heavily on the saturation of the cake. Capillary pressure and tensile strength as a function of the liquid saturation is shown on a diagram (for limestone filtration).

5.6 H.A. Hamza

Filtration and Filter Media; CANMET Report 77-9, Energy, Mines and Resources Canada; Aug. 1977.

This report presents a detailed review of the application and operational aspects of the filtration process. It outlines criteria that should be applied for selecting filters and filter-media for various systems and slurry characteristics.

5.7 H. Anlauf

Entfeuchtung von Filterkuchen bei der Vakuum-Druck und Druck/Vakuum Filtration.

Dewatering of Filter Cake During Vacuum, Pressure and Pressure/Vacuum Filtration.

Fortschritt - Berichte VDI - Verlag Reihe 3: Verfahrenstechniki; No. 114, 1986; 217 pages.

This is a monography summarizing recent theoretical and experimental developments of filtration methods. It is oriented toward mineral processing. Described is: 1) experimental equipment used, 2) characteristics of material from the filtration point of view, 3) theory of dewatering, 4) gas flow and consumption, 5) consumption of energy. Exact calculation of the capillary fluid transport through discrete, dispersed, porous systems of solids is not possible to date.

Models used have to be based on simplifying assumptions where the bulk material is ideally homogeneous isotropic and incompressible. These idealised models are difficult to apply to real, technically obtained filter cakes. In particular, for grain size under 0.1 mm the condition of incompressibility is far from reality. Extensive laboratory experiments served in this work to find out where and to what extent selected simplifications are admissible and can be used for calculations within a needed degree of exactitude. Disturbing effects like sedimentation/classification, cracks on cake and boundary effects, influence of filter-media, thermic effects - are discussed. Porosity distribution, specific permeability, filter media resistance to flow, particle size, air pressure and their influence are discussed as well. Saturation, capillary pressure, types and time of dewatering process, thickness of cake and their influence on residual moisture and on the process of dewatering are considered. Permeability of cake, porosity, resistance of filter media to liquid flow cannot be calculated from size distribution and other material characteristics. They have to be measured. The same is valid for capillary pressure distribution. The residual moisture could be calculated with the help of a model of kinetics. There is no "piston" liquid front during dewatering but particular "thick" pores are emptied first. The flow of liquid can be calculated when a capillary pressure distribution is introduced. Calculation of the air flow through a partially dewatered bulk material is possible with the use of the conception of relative permeability. Air has to be considered as compressible. Permeability to gas changes as the dewatering progresses.

- 5.8 L.T. Fan, S.H. Hwang, R. Nassar, S.T. Chou
 An Experimental Study of Deep-Bed Filtration: Stochastic Analysis;
 Powder Technology, 44, 1985; pp. 1-11.

Deep bed filters also known as granular filters are extensively used in purification of potable water. Pressure drop and effluent concentration were measured as a function of filtration time. Performance of a deep-bed filter depends on a large number of variables

including the size distribution of suspended solids, suspension concentration, filtration rate and bed characteristics.

Stochastic models like linear, pure birth model, linear, birth-death and second-order pure birth model have been developed to simulate the pressure drop within the bed. Although this work does not apply to dewatering by continuous filtration processes as used in mineral processing nor to water migration in concentrates, it shows a different, not traditional approach to similar processes.

5.9 R.C. Emmett, D.A. Dahlstrom

Steam Drying of Filter Cake; Chemical Engineering Progress, Vol. 68, No. 1; January 1978; pp. 51-55.

Moisture content of a filter cake can be correlated against an "approach factor". It depends on dewatering time and weight of dry cake solids per unit area per revolution. The passage of steam through a filter cake lowers viscosity thereby lowering the residual moisture content at very good thermal efficiencies. In most applications, cake temperatures of about 75°C are reached in a few seconds. Moisture removal ranges from 20% to more than 90%. For coarse iron concentrates in cold climates, the hood in a pilot plant was partitioned so that room temperature air would be pulled through the cake for final adiabatic cooling on the filter. The final moisture is directly dependent on the volume of cooling air pulled through the cake after steaming. There was never a problem to obtain less than 0.5% final moisture. As a maximum only 125 lb of steam per long ton of dry solids (55.80 kg/tonne) is needed. Thermal efficiencies are very high. In many cases moisture removal would approximate 1 kg of water removed per kg of steam applied. The cooled product is about 40 to 75°C. Temperature of steam used was 130-140°C.

- 5.10 K.W. Daykin, E.M. Healey, D.S. Parker, M.J. Parkinson
Steam-Assisted Vacuum Filtration; Mine and Quarry; Vol. 7, No. 3;
March 1978; pp. 59-65.

This article reviews briefly current knowledge of the science and application of the steam-assisted vacuum filtration process. Filtered coal cakes without steam application contain typically 22-30% water. Using steam a further reduction of 5-9 percentage points can be obtained. The effect of reducing the viscosity (μ) and/or the surface tension (σ) can be described by the Silverblatt & Dahlstrom empirical equation. Evaporation from the hot cake after steam application was found to give a one percentage point reduction in moisture content. While laboratory-scale tests can give a good indication of the moisture reduction likely to be achieved, results of such experiments cannot be used to predict steam consumption on a full-scale plant. Complementary reduction of moisture can be achieved by: 1) application of steam to the slurry as it is fed - this prevents air from blocking the capillaries within the cake; 2) extension of steaming time so that a small quantity of steam passes right through the cake immediately after steaming; 3) drawing hot air through the cake immediately after steaming; 4) drawing ambient air through the hot cake. In an efficient commercial plant where the filter is in good mechanical condition and steam supply controlled, approximately 1.2 tonnes of steam is required to remove one tonne of water.

SECTION 6. SURFACTANTS, FLOCCULATION

6.1 F. Halverson, H.P. Panzer

Flocculation Agents; Reprint from Kirk-Othmer: Encyclopedia of Chemical Technology, Vol.; 10, Third Edition; 1980.

Described is the mechanics of flocculation, criteria for flocculant selection and for optimum flocculant dosage. Flocculant selection has to be done by laboratory testing. It has to be confirmed at a full-scale plant because laboratory tests rarely reflect the dynamics of commercial scale processes. Measurement of zeta potential may be useful in some situations. In others, compositional heterogeneity of the substrate imposes difficulties in interpretation and some form of jar test is the only way to proceed. For solids separation via vacuum filtration a Buchner funnel test is used. As a supplement to this method the filter-leaf test and the capillary suction time test are used. Several types of flocculating agents/inorganic materials, cationic, nonionic, anionic, polyampholytes, derived from natural products and their possible action mechanics are described.

6.2 J.C. Boeglin

Progrès réalisés dans la séparation des phases solide - liquide et le séchage des boxes par centrifugation et utilisation de polymères organiques de synthèse.

Progress Achieved in the Separation of Solids from Liquid and Dewatering Slimes by Centrifuging and Use of Synthetic Organic Polymers.

Revue de l'industrie minière - Mines; juillet 1971; pp. 517-529.

Techniques of phase separation (solid-liquid) by centrifuging started to develop rapidly only after synthetic flocculants were introduced to the industry in the early 1960's. Using them it was possible to achieve total extraction of solid matter on continuous bowl centrifuges. Description of three types of bowl centrifuges and industrial results obtained on one of them when dewatering different slimes and using different flocculants is given.

6.3 M.A. Kessic

Ion Exchange and Dewaterability of Clay Sludges; International Journal of Mineral Processing; 6(1980) 277-283; pp. 277-283.

Oil sands clay tailings and montmorillonite gel were effectively dewatered by conversion to calcium form by ion exchange. They were mixed with Ca(OH)_2 and afterwards subjected to freezing and thawing or in the case of montmorillonite, in a separate test, also using centrifuging.

Maximum dewaterability coincides with maximum replacement of sodium ion by calcium ion. The volume of the material can be reduced (be dewatering) by a factor of 2.5 while sodium hydroxide and water can be recovered during this process.

6.4 K. Brennecke, M. Clement, H. Travinski

Beitrag zur Entwässerung von mineralischen Schlämmen in Vollmantel-Schleudern mittels polymerer Flockungshilfsmittel.
Contribution to Dewatering of Mineral Slimes in Bowl Centrifuges by Application of Polymer Flocculation Aid.
Glückauf-Forschungshefte, Feb. 1973.

Without flocculants, when the speed of the centrifuge increases, the solid concentration in the overflow diminishes, while the solid recovery increases. The residual moisture in the cake decreases by very little. The highest recoveries are attained with low concentrations of solids in the feed or low quantity of feed in time. The lowest residual moisture is when the concentration of solids in the feed is high and the capacity kept high. In general, the increase of speed results in increasing of the equivalent clarification surface. The addition of polymers increases the residual moisture, probably because water is bound inside flocs. However, increasing speed may, for some flocculants, decrease residual moisture below the level which would be achieved when no flocculants are added. With the addition of polymers the recovery of solids increases drastically. In order to get the best results for a given material, optimum kind and concentration of polymers has to be used and optimum speed applied.

6.5 G.C. Sresty, P. Somasundaran

Selective Flocculation of Synthetic Mineral Mixtures Using Modified Polymers; International Journal of Chemical Processing; 6 1980; pp. 303-320.

Selective flocculation may be used for sub-sieve size ranges, where other techniques are inefficient. Selectivity may be achieved either by altering the interfaced potential of the mineral to create desired electrical interaction between the polymer and mineral or by incorporating suitable functional groups into the polymer. Minus 20 μm fraction of hematite-quartz mixture was tested in test tubes, using sodium polystyrenesulfonate. Separation index achieved was about 0.5 (1.0 refers to complete separation, 0.0 refers to no separation). Cleaning of the flocculated product by re-dispersion in water is essential for obtaining satisfactory separation.

6.6 P. Belanger

Effets du Réactif Nalco 8815 sur la concentration d'un minéral de la Compagnie Québec Cartier.

Effects of Agent Nalco 885 on the Concentration of the Q.C.M. Ore. Ministère des Richesses naturelles, C.R.M. Alchem Inc., 1979.

The use of Nalco 8815 as a filter aid reduces the residual moisture in the filter cake. The filtrate water returned to the water circuit of the concentrator carrying small amounts of the agent has a tendency to improve the iron unit recovery of the gravity separation. Changes of viscosity and surface tension as a function of the agent concentration are given.

6.7 A. Tanguay

Filtering and Investigation Testwork Report, Quebec Cartier Mining Company, 1980.

The feasibility and potentials of changing the present filter cloth and adding a flocculant to filter feed to decrease the moisture content

have been investigated on an industrial scale of a mill line. These tests did not fully confirm bench-scale tests carried out previously.

6.8 P. Boulanger, D. Trudel

Filter Aids Evaluation; Report of CALGON Canada on research carried out for Québec Cartier Mines; March 7, 1978.

Sixteen different filter media and two promising chemicals were tested to determine the possibility of reducing the concentrate moisture. Three filter media and two chemicals gave good results, permitting the reduction of the moisture level at about 50% without using steam.

6.9 J. Leung, W. Cameron

Investigation to Improve the Dewatering of the Thickeners in QCM Iron Ore Plant; Division Report MSL 87-23 (IR), CANMET, Energy, Mines and Resources Canada; January 1987.

Investigations proved that it is possible to improve the dewatering results of thickeners at Mount Wright concentrator by the use of anionic polyacrylamide flocculants. With flocculant addition of only 85 mg/t, the settling rate improved by 2-14 times and the amount of supernatant increases up to 30%. Anionic polymers are more cost-effective than their cationic counterparts. Flocculant additions did not improve the supernatant quality.

The report is accompanied by a mineralogical Image Analysis Study of Samples from Q.C.M. carried out by W. Petruk, CANMET.

SECTION 7. SEQUESTERING WATER

7.1 J.D. Sheppard, J.C.T. Kwak, A. Latiff Ayub

The Role of Colloid Science in Peat Dewaterings: Principles and Dewatering Studies; Chapter of the book edited by C.H. Fuchsman; Peat and Water: Aspects of Water Retention and Dewatering in Peat; Elsevier Applied Science Publishers Ltd. 1986.

Principles of colloid science relative to peat/water systems are described. Water in peat which is to be removed in practical dewatering operations will always fall in the category of weakly bound water, i.e., mechanically entrained and capillary water. Anionic surfactants do not improve dewatering-by-pressing characteristics. Cationic surfactants result in marked improvement of the amount of water removed. There is an optimum amount of additive. Two layers of water bound by adsorption would contain 0.2 g H₂O/g dry peat, or 17% of total weight. If there were 10 layers of adsorbed water they would give only 1 g H₂O/g dry peat, (i.e., 50% of total weight). However, this is considered by authors as clearly too high. The total specific surface area of peat for this calculation is assumed to be about 300 m²/g. Similarly the upper limit of water bound chemically is probably about 30%. Modification of the hydrophilicity/hydrophobicity of peat by means of surfactants changes interfacial tensions and may be effective in dewatering/moisturizing processes. Natural peat is mainly hydrophobic with some hydrophilic sites (COO⁻, phenolic OH, etc.).

7.2 C.H. Fuchsman

Peat Industrial Chemistry and Technology; Academic Press, New York, 1980.

This book is a monograph describing peat mainly from the chemical point of view. Much less attention is paid to physical characteristics including water retention properties. Chemical characterization of peat, its pyrolysis, chemical methods of peat analyses and a list of references including about 500 items are given.

7.3

Calcium and Sodium Bentonite Uses and Consumption; Industrial Minerals; December 1972; pp. 21-35.

Different types of bentonite are described. The use and role of bentonite in iron ore pellets production is presented, possible substitutes for bentonite mentioned. This is a very good complement to [7.6].

7.4 J.M. Middleton

Foundary Binder; Industrial Minerals; Oct. 1969; pp. 17-21.

Bonding properties of bentonite, swelling capacities, methods of converting calcium (non swelling) to sodium bentonite are discussed.

7.5 G.B. Sowers, G.F. Sowers

Introductory Soil Mechanics and Foundations; MacMillan Co.; 1970.

One chapter is devoted to soil stabilization. Discussed are such methods as moisture holding, retention of moisture in soil, moisture resisting, precaution of moisture from entering soil, cementing, binding the particles together without their alteration, void filling, mechanical stabilization, improving the soil gradation, physico-chemical alteration, changing the clay-mineral adsorbed-water system. Effects of admixtures such as sodium and calcium chlorides, portland cement, lime-fly ash, organic monomers, chrome-lignin, dispersing agents, etc., are described.

7.6 C.W. Davis, H.C. Vacher, J.E. Conley

Bentonite: Its Properties, Mining, Preparation and Utilization; U.S. Dept. of the Interior, Bureau of Mines Tech. Paper 609; Washington 1940.

This is a monography describing water retention properties as well as many other physical and physio-chemical properties of bentonite.

Although old and out of date in many aspects, together with [7.3] and [7.4] it gives a comprehensive picture of bentonite characteristics and use.

SECTION 8. PELLETIZING

8.1 I. Iwasaki, J.D. Letterstom, E.M. Kalar

Removal of Fatty Acid Coatings From Iron Oxide Surfaces and its Effect on the Duplex Flotation Process and on Pelletizing; Transaction Society of Mining Engineers; Sept. 1967; pp. 304-312.

Fatty acid collector used for flotation forms coatings which very often disturb pelletizing. These coatings may be successfully removed using a combination of chemical reagents or activated carbon.

8.2 D.A. Rice, R.L. Stone

Influence of Plant Water Chemistry on the Strength of Unfired Pellets; Society of Mining Engineers; AIME Transactions; Vol. 252; March 1971; pp. 1-6.

Unfired pellets made of filter cakes from which soluble salts were removed proved to be 50-100% stronger than usual unfired pellets containing the salt. Calcium and magnesium salts are probably the most detrimental in the plant circuit. Ca, Mg and other polyvalent cations probably exchange ions for lower-valence cations in bentonite and therefore destroy the electrostatic-charge bonding in the green pellets. Probable mechanics by which bonding takes place in pellets when bentonite is used is described. A clay particle can have both a positive charge at the exposed surface formed by cutting through the tetrahedral and octahedral sheets as well as a negative charge on the surfaces parallel to these sheets. Influence of zeta-potential of bentonite on the strength of pellets is mentioned.

8.3 K.E. Merklin, M.H. Childs

Some Factors Influencing the Physical Qualities of Iron Ore Pellets; AIME Transactions (Mining) 1962; Vol. 223; pp. 491-498.

Specific surface area, increased addition of bentonite, addition of soda ash and coal, ball size, ball forming time as parameters

influencing physical qualities of iron ore pellets are discussed. In some plants chips screened from the fired pellets are ground finer and added to the concentrates before balling. This material reduces the effect of thermal shock during firing. Types of pellet degradation are described.

8.4 R.L. Stone

Relation Between the Zeta Potential of Bentonite and the Strength of Unfired Pellets; Society of Mining Engineers, Transactions Sept. 1967; pp. 284-292.

The possibility of rating bentonites on the basis of zeta potential was investigated. For comparison, these bentonites were also rated by conventional tests including colloid content, barrel yield, pH, chemical analysis and physical tests on green and dry pellets. The zeta potential is a reliable index of the strengthening ability of a bentonite, in particular as concerns dry strength of pellets. Zeta potential measurement and sample preparation to this measurement is described. The zeta potential on the bentonite and the strength of the resulting pellets can be altered by the addition of selected chemicals. The changes in zeta potential can probably be related to the capacity of anions and cations of the added chemicals to increase or decrease the thickness of the diffuse double layer of the bentonite.

8.5 K. Taguchi, T. Uenalea, S. Inaba, H. Isalco, I. Mirugudu, K. Umeji

Development of Crushed Pellets at Kaliogawa Works; Mining Eng.; Dec. 1985; pp. 1385-1390.

Production of crushed pellets aims at increasing permeability in the blast furnace. Large "jumbo" pellets are produced and then crushed in crushers. The immediate effect results in a lowering of the coke rate.

8.6 H.B. Ries

Zur Praxis der Pelleterzeugung.

Pellet Production in Practice.

Aufbereitungs - Technik, Vol. 22(4); 1981; pp. 209-220.

Thirty-three goals of pelletizing different materials are shown. Influence of construction of pelletizing mixers and plates and of their operation parameters on the dimensions and characteristics of pellets are described.

8.7 A.K. Kuriakose, D.H.H. Quon, K.E. Bell, J.A. Soles

Extrusion and Induration of Iron Ore Using Polymers and Calcium Carbonate as Plasticizer/Bond; Division Report MSL 86-13 (OP&J), CANMET, Energy, Mines and Resources Canada, Published in Process Mineralogy VI, Edited by R.D. Hagni; Publ. of the Metallurgical Society, 1986; pp. 485-498.

A method is described by which pellets are manufactured from iron ore concentrates by extrusion using organic polymers and calcium carbonate as plasticizers and binders. Binders for iron ore extrusion can strongly affect the rheology of the liquid phase. They increase the viscosity and change the flow characteristics from Newtonian to pseudoplastic in most cases. With some binders gels can develop under various conditions. The rheology of the solution directly affects the behaviour of suspensions and pastes formed by adding particulates to the solution. The applicability of a given binder for a specific process is very much dependent on the rheological characteristics of the binder solution. The organic binders selected for this study were carboxymethyl cellulose, methyl cellulose, hydroxyethyl cellulose and ammonium alginate. Inorganic binders were calcium oxide, calcium hydroxide and calcium carbonate. The plasticity of the iron ore with binder or binder system was first determined by using a Brabender Plastograph. This equipment measures the plasticity of the material in terms of consistency which is a measure of the viscosity of the flowing plastic dispersion.

8.8 D.H.H. Quon, K.E. Bell

Vacuum Extrusion of Mt. Wright Iron Ore with Organic Polymers and Bentonite as Plasticizer; Division Report MRP/MSL 85-72 (IR), CANMET, Energy, Mines and Resources Canada; May 1985.

General characteristics of binders are described. The precise mechanism by which bentonite improves ball strength and the physical properties that make a particular bentonite a good binder are not completely known yet. The electrokinetic charge and colloid content, considered together, give a useful guide as to the pelletizing properties of a given bentonite. The following inorganic binders were used: bentonite, sodium and calcium carbonates, gypsum, calcium hydroxide, calcium oxide and Nyacol (a colloidal silicate). The organic binders employed were lignosulphonates, starch, acrylics, sodium, carboxymethyl cellulose, methyl cellulose, hydroxyethyl cellulose, sodium and ammonium alginates, Elvanol, stearic acid, latex, lactose and Liqui-Lass. Determining the plasticity with a Brabender Plastograph is described. The use of organic binders reduces flux and coke requirements by eliminating excess impurities in the iron pellets. One of the disadvantages of organic binders is their thermal decomposition at relatively low temperature which may be detrimental for the strength of fired pellets.

4. LONG RANGE PROGRAM FOR FURTHER INVESTIGATIONS

1. Tests needed for drawing the capillary pressure curve of iron ore concentrates
 - 1.1 Measurements carried out with the pressure apparatus.
 - 1.2 Measurements carried out with a centrifuge.
2. Measuring the specific surface area, porosity, hydrophilicity/hydrophobicity.
3. Dewatering by filtration tests.
 - 3.1 Small scale vacuum filtration tests
 - 3.1.1 Without filter aid.
 - 3.1.2 With surfactant filter aids, followed by transportability tests.
 - 3.1.3 With steam aid.
 - 3.1.4 With steam and surfactants, followed by transportability tests.
 - 3.2 Small pilot scale continuous vacuum filtration tests without and with filter aids, combined with transportability tests.
 - 3.3 Small scale pressure (and hyperbar) filtration tests without and with aids.
 - 3.4 Small pilot scale pressure (and hyperbar) filtration tests without and with aid.
4. Centrifuge tests (detailed program depending on results of tests as under items 1 and 3).

5. Tests of draining enhanced by shaking and vibration (detailed program depending on results of tests as under items 1 and 4).
6. Testing the relationship between the specific surface area, attrition, regrinding and the residual moisture content in concentrates after dewatering.
7. Testing the influence of circuit water characteristics on dewatering/water migration.
8. Establishing an optimum dewatering régime for iron ore concentrates.